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MODELING ELECTRON CLOUD EFFECTS IN HEAVY ION ACCELERATORS*

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OUTLINE

- Distinguishing features of ecloud issues for HIF
- Our plan for self-consistent modeling
- Example with secondary-electron sources
- Electron effects on ions: simulations with specified electron distributions
- Preliminary results for averaged electron dynamics
- Summary

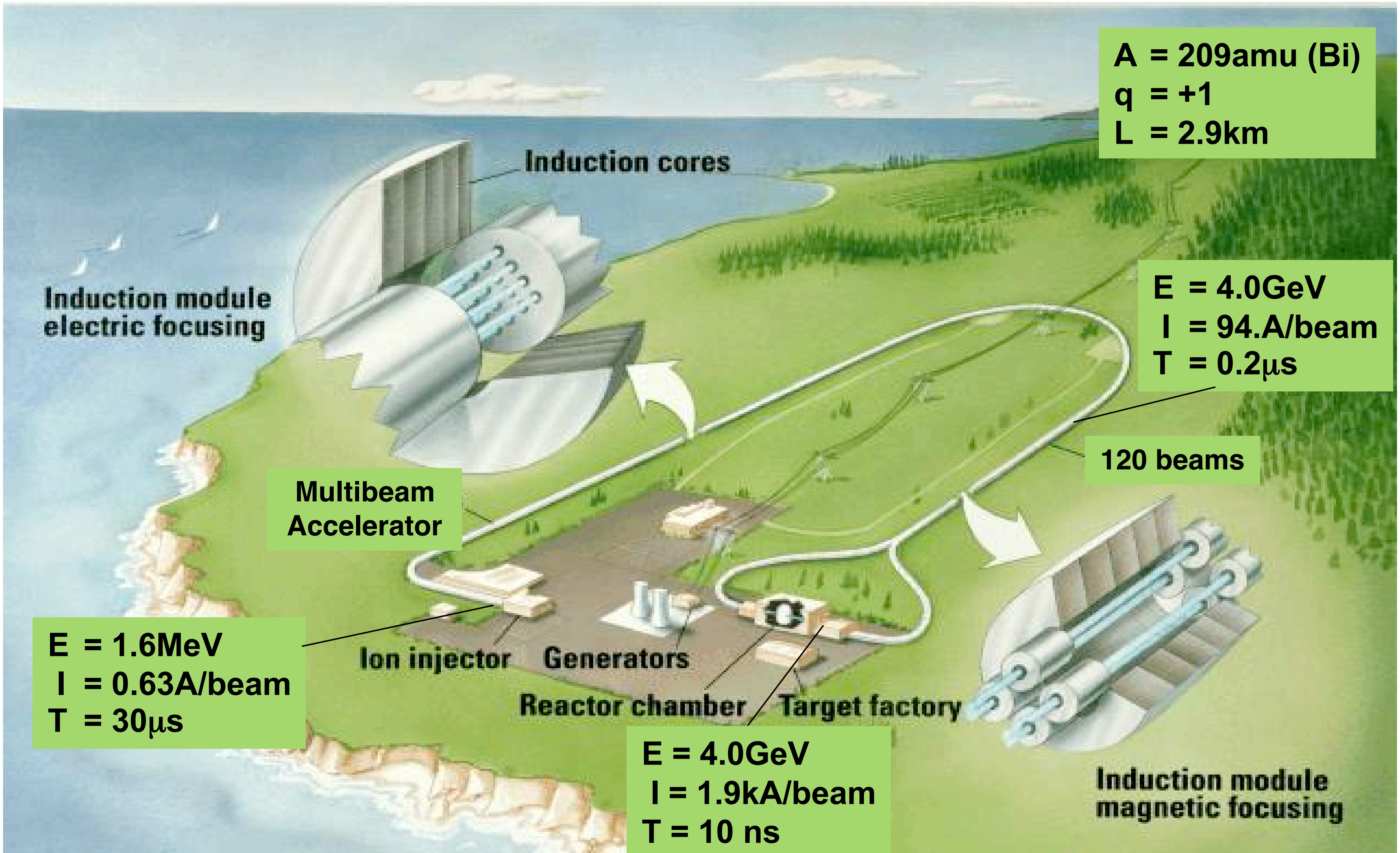
Related papers:

Molvik et al (Monday p.m.)

Vay et al (Tues. p.m.)

Stoltz et al (next paper)

Artist's Conception of an HIF Power Plant on a few km^2 site



HIF accelerators have distinguishing features that impact electron cloud issues

Compared to other accelerator applications:

- Many common issues and concerns, but also application-specific features
- Distinguishing aspects of HIF accelerators (U.S. main line with magnetic quadrupole focusing):
  - Linac with high line charge density
  - Induction accelerator --
    - hard to clean beam pipe ⇒ large neutral emission coefficient at pipe wall (> 10^3)
    - Beam pipe only in quad magnets ⇒ scrape-off only in quads
  - Economic mandate to maximally fill beam pipe
  - Large fraction of length occupied by quadrupoles (>50% at injector end)
  - Long(ish) pulses -- multi-μs at injector end

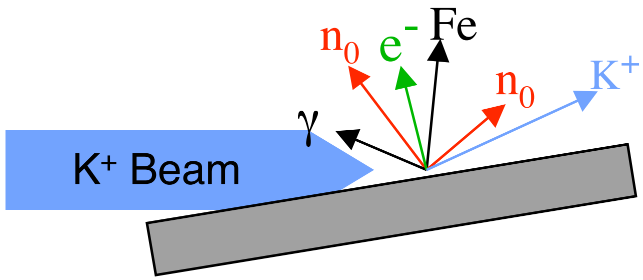
Consequences 1

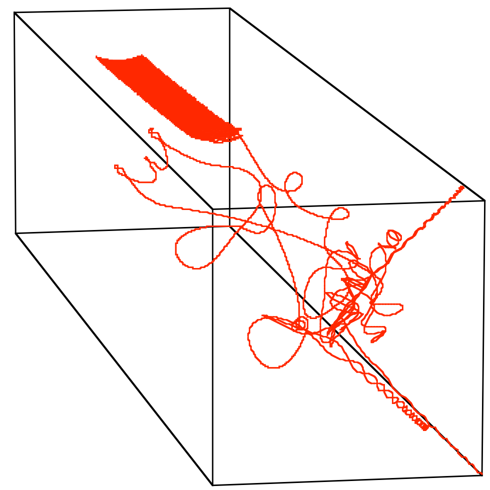
- Linac, so multiturn resonance not an issue
  - But long pulse $\Rightarrow$ still instability if e-e SEY > 1
- Electrons largely confined to the quadrupole in which they are born, and electron density smaller in gaps than in quads; consequences of:
  - Beam pipe only in quads; strongly magnetized electrons
  - Time to drift out of a quad ~ pulse durations
  - Accelerating gaps between quads, which enable electrons to overcome space charge potential

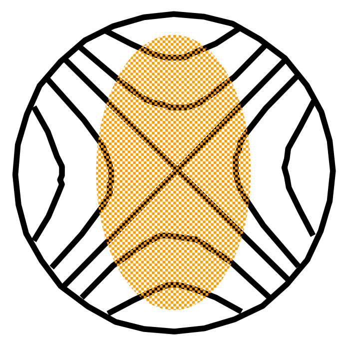
  Important implications for potential instabilities.
- Filling pipe as much as possible $\Rightarrow$ ion scrape-off major source of electrons

Consequences 2: Electrons from gas released at walls in quads dominate

- e^- from ionization of neutrals released from walls dominates for long (multi-μs) pulses.
  - Born trapped by beam potential
    - Bounce radially
    - Drift axially
    - Acquire enough energy in gap to escape
    - Hence τ_e ~ time to drift through 1 quad
- For shorter pulses: secondary electrons from ion bombardment
  - Nominal lifetime 1 transit (during beam flattop)
  - e^- from scrapeoff of beam ions: mainly on field lines that stay close to wall.
  - For small fraction born on field lines that penetrate deep into interior, collisionless pitch-angle scattering (nonadiabaticity) can make lifetime much longer

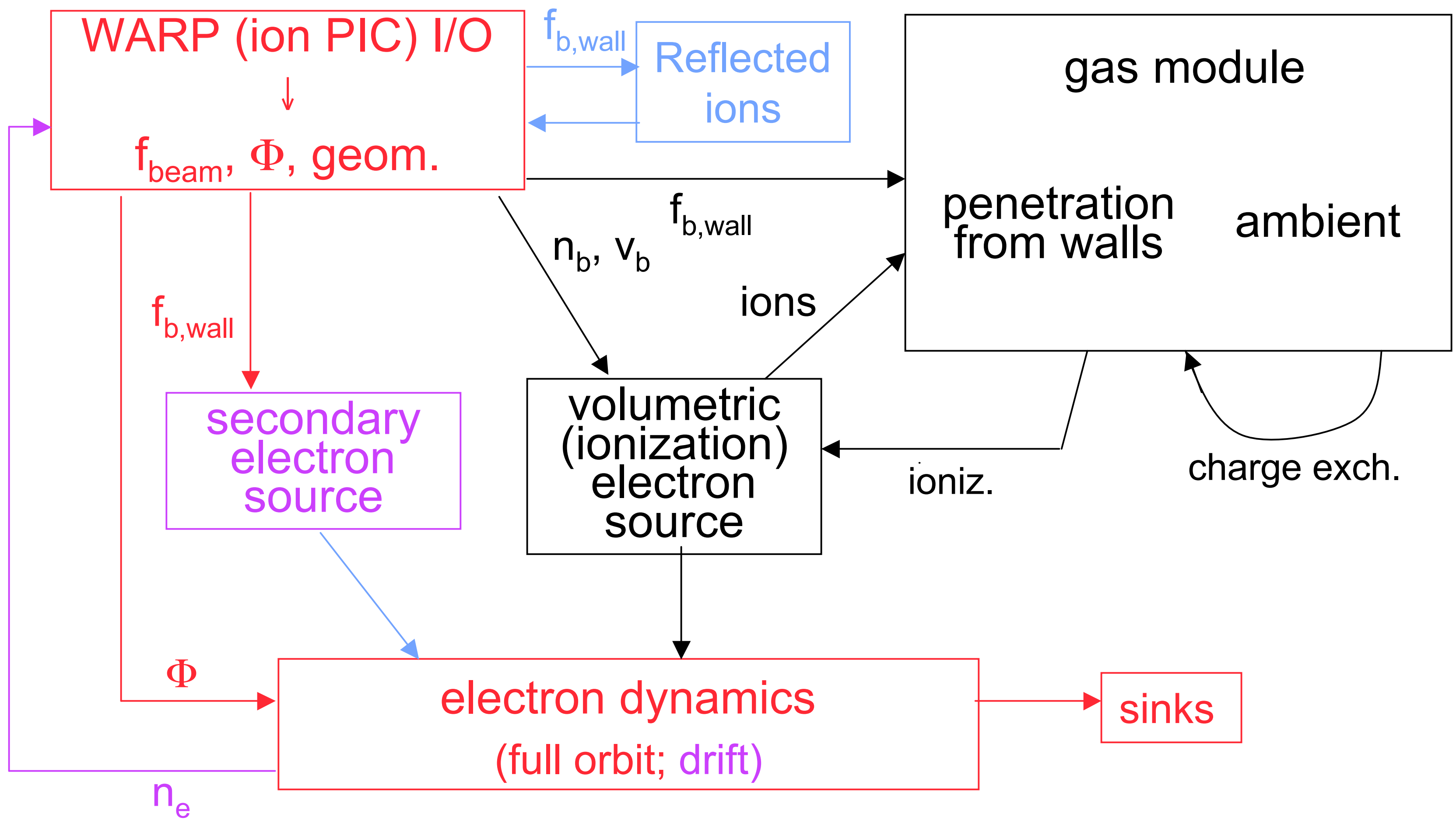






Toward a self-consistent model of electron effects

- Plan for self-consistent electron physics modules for WARP



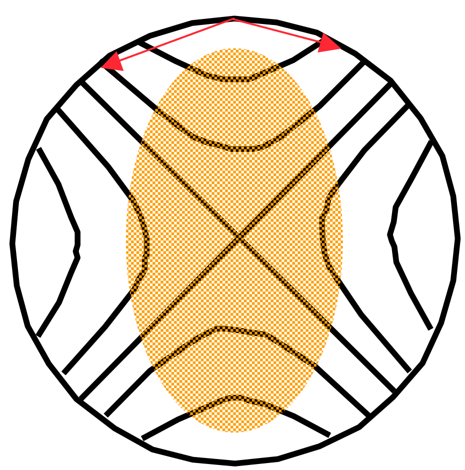
- Key: operational; implemented, testing; partially implemented; offline development

Example of current capability: secondary electrons from primary and secondary ion bombardment

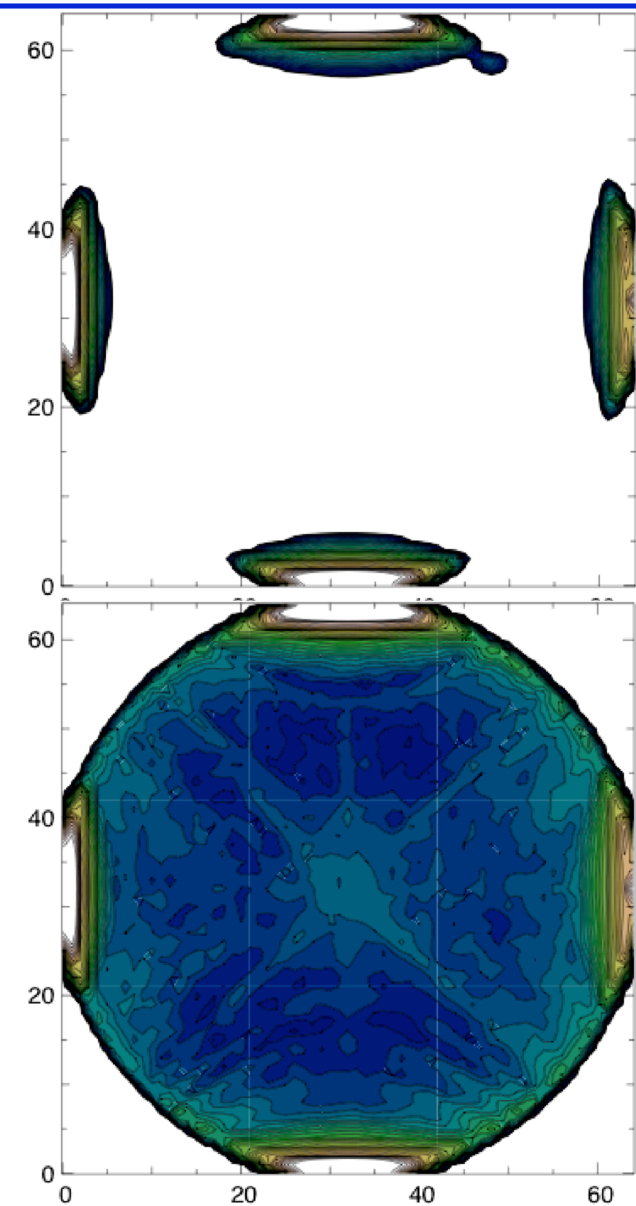
- WARP ion slice simulation, 400,000 ions
  - 100 lattice-period transport system (no acceleration)
  - Misaligned magnets (500 μm) to exaggerate beam scrapeoff
- Gather data for ions impacting wall (6282 ions), and calculate:
  - Secondary electrons produced (from simple fit to Molvik et al data)
  - Scattered ion population (3629 ions), from TRIM Monte-Carlo code
- Follow the scattered ions in 3-D Warp until they next impact wall.
- Calculate secondary electrons produced by those ions
- Follow dynamics of electrons produced by primary and scattered ion impacts with 3-D WARP; accumulate electron charge density

Calculation of n_e from secondary electrons shows importance of following scattered ions

- Full-orbit calculations of electrons born as secondaries from impact of lost beam ions
  - Based on initial ion-wall impacts: cloud confined to wall near beam ellipse tips



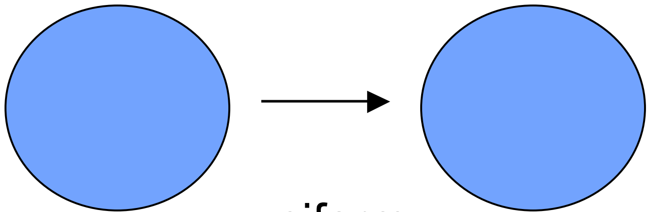
  - Dramatic difference if we follow scattered ions and add in the secondary electrons THEY produce



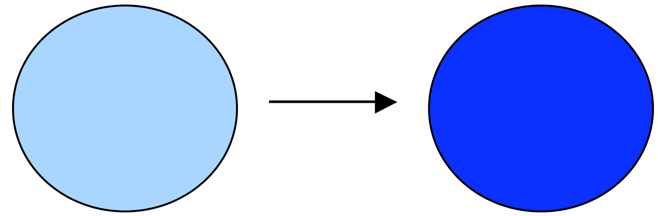
Ion simulations with legislated electron clouds show level of acceptable density and highlight areas for concern

- Perform ion simulations with legislated negative charge distributions to mock up electrons
  - Const n_e
  - Random cloud variations
  - Sinusoidal cloud variations, with period chosen to match a beam natural mode
    - Breathing
    - Centroid oscillations (dipole mode)
    - Elliptical distortion oscillations (quadrupole mode)
  - Types of electron cloud variations studied (in all cases the perturbation is axially constant within a quadrupole, and varies from quad to quad):

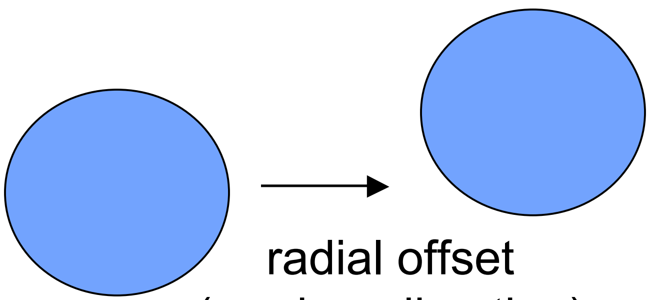
Types of electron cloud perturbations specified



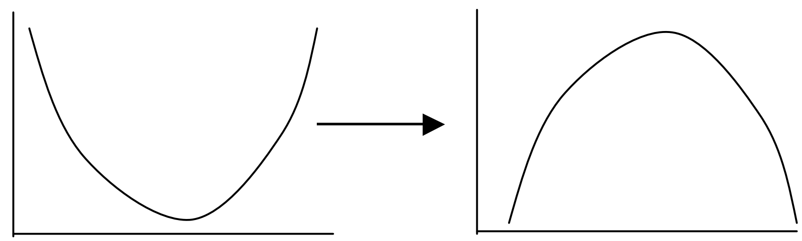
uniform



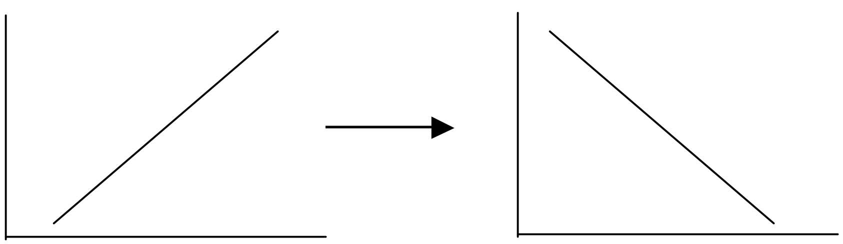
amplitude



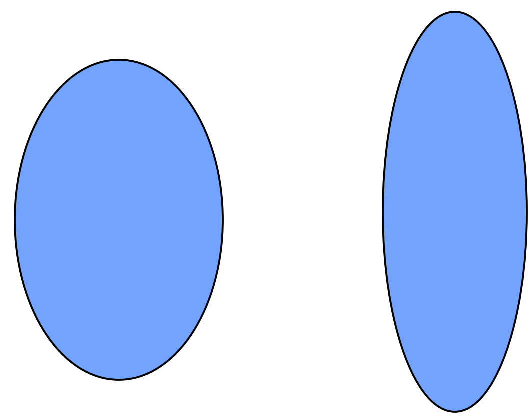
radial offset
(random direction)



radial shape variation

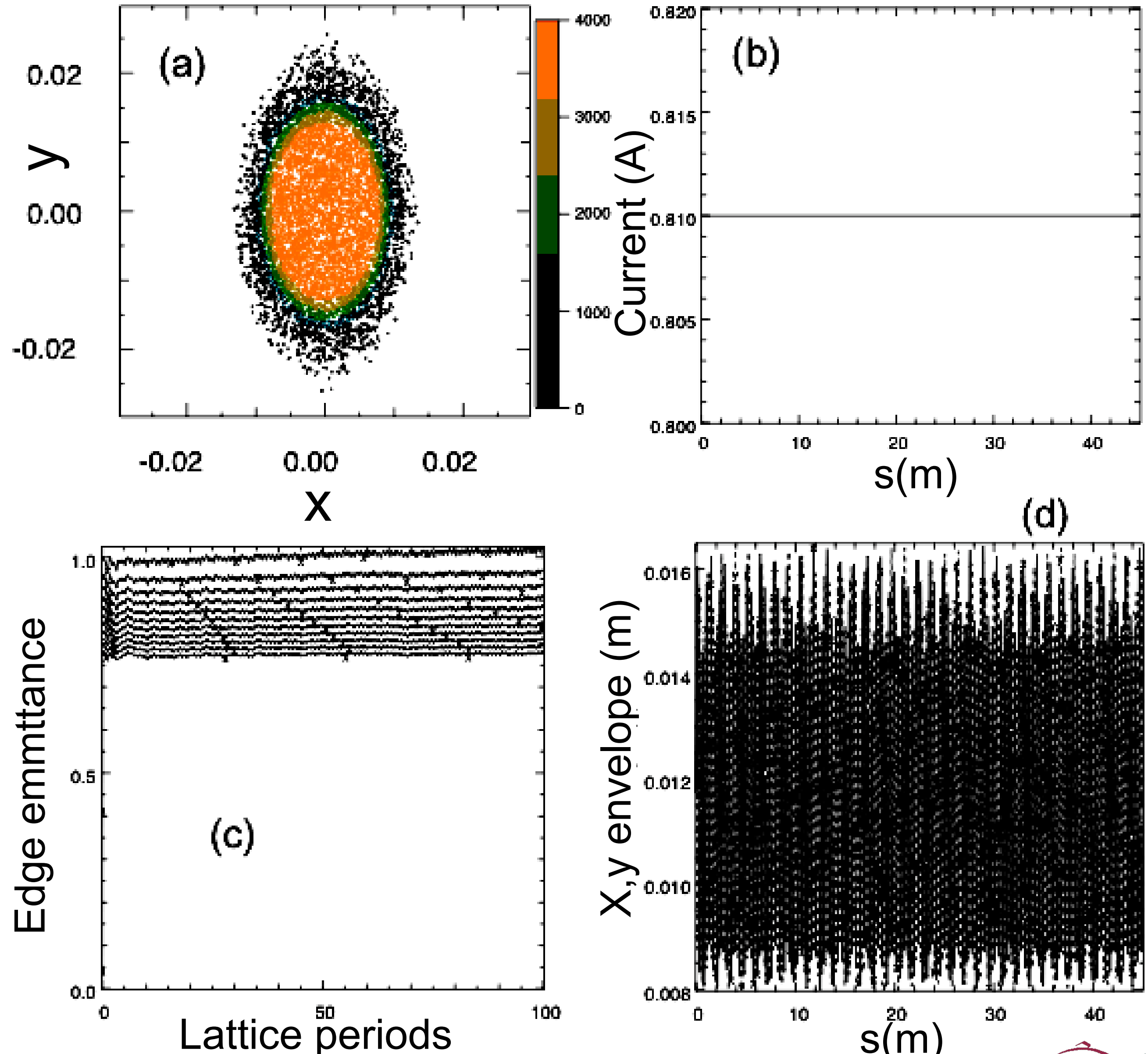


ramp (rotating)

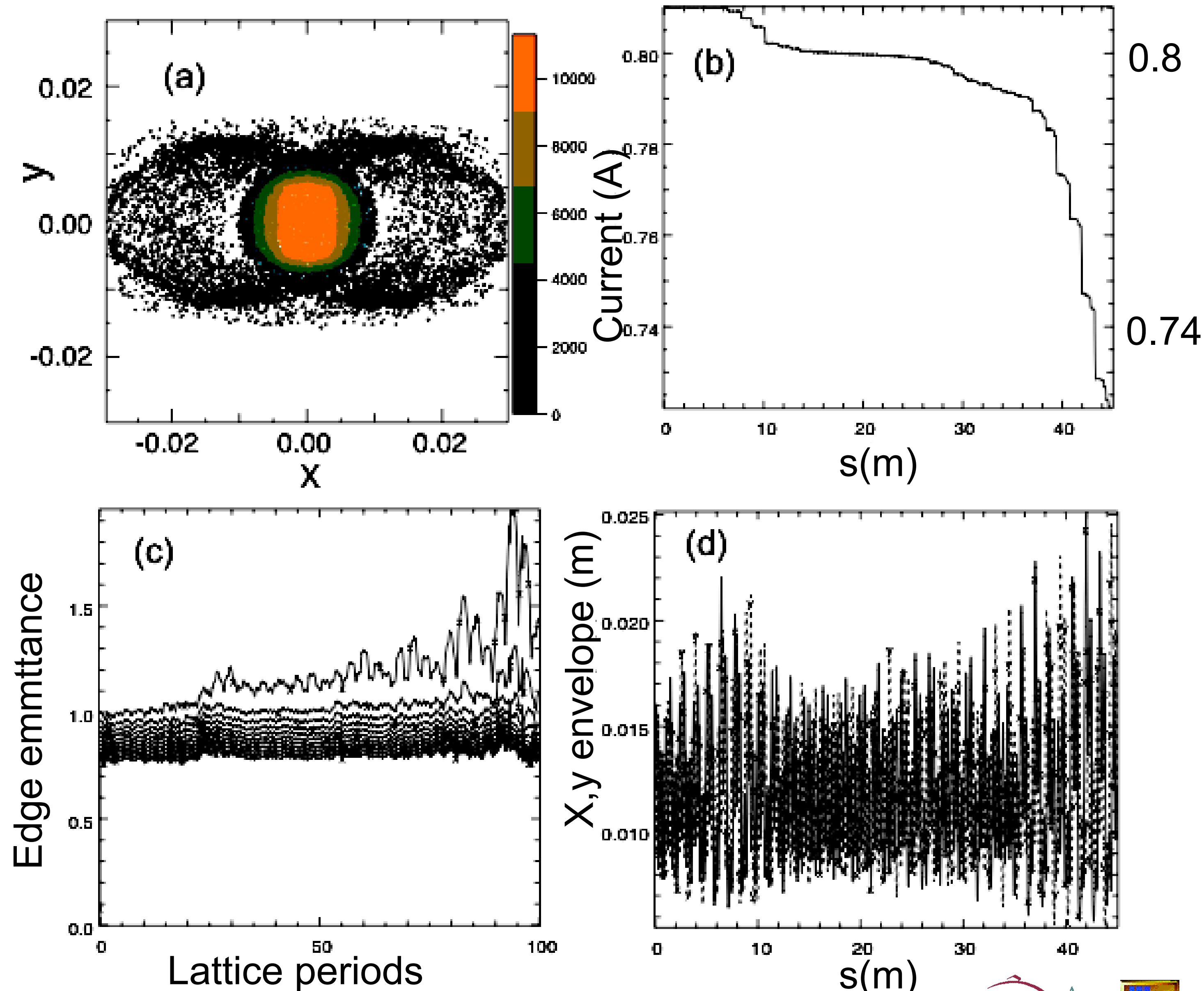


ellipticity

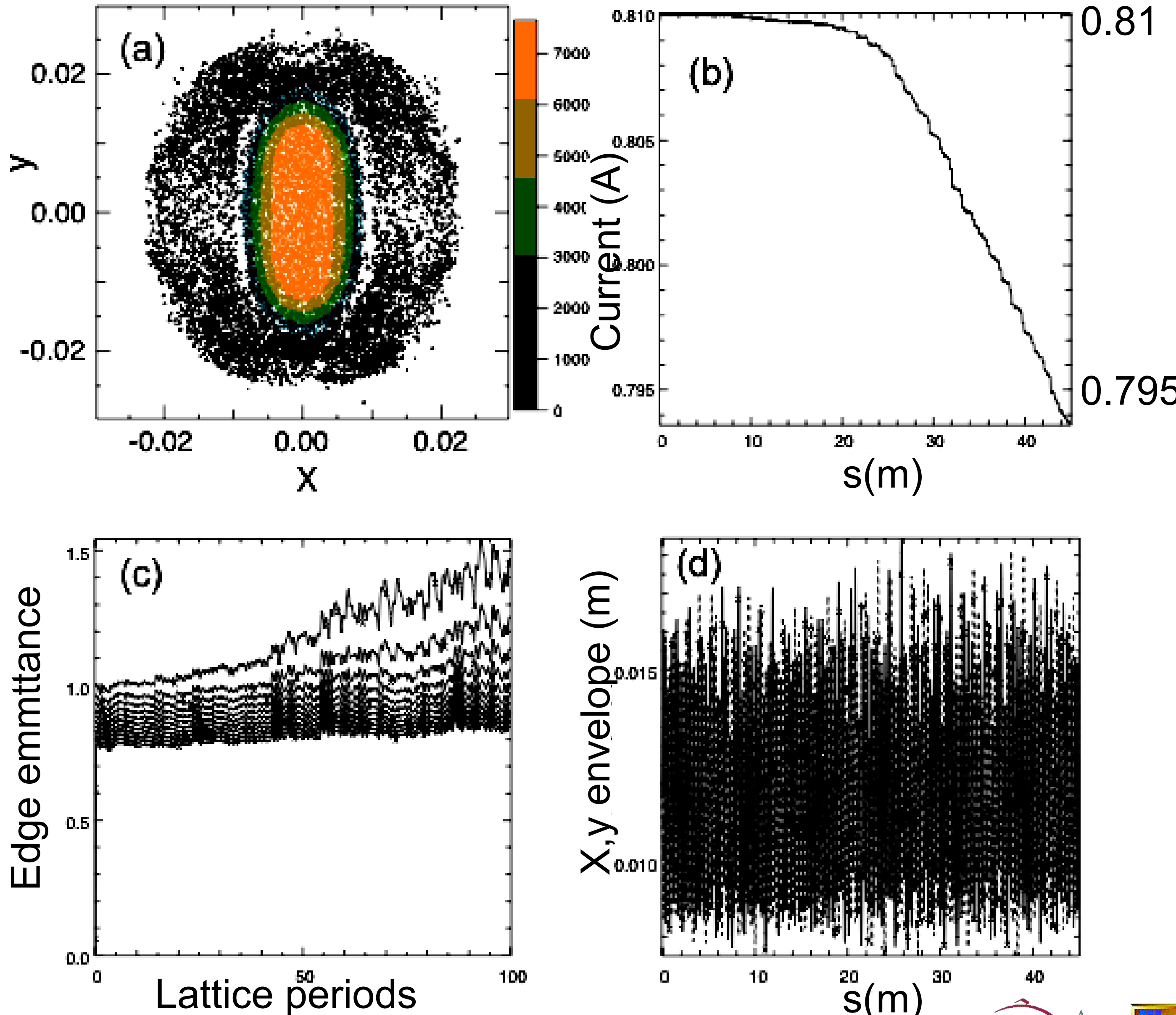
20% constant n_e has little effect



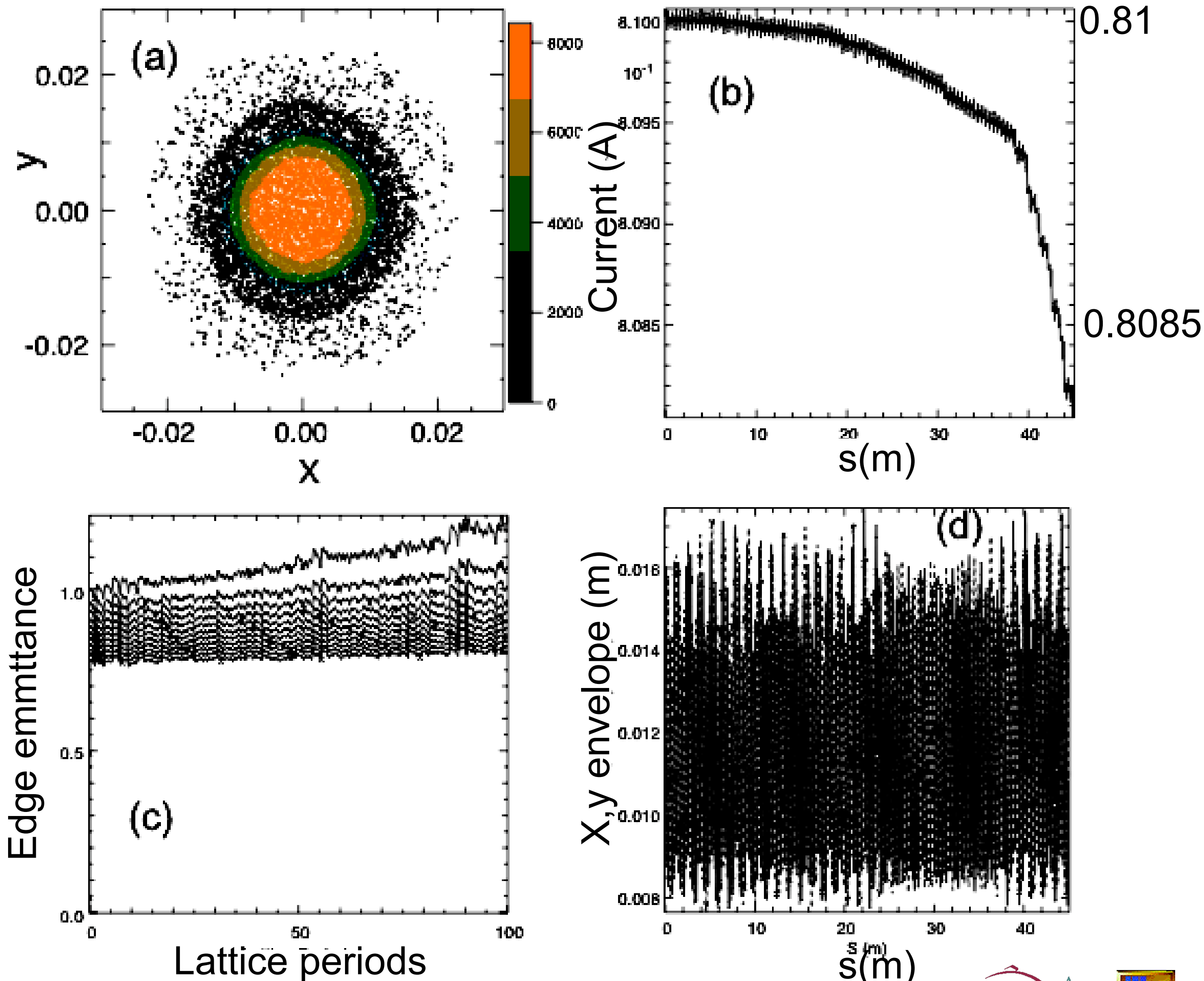
20% mean, 0-40% random n_e produces significant beam loss, envelope growth, halo



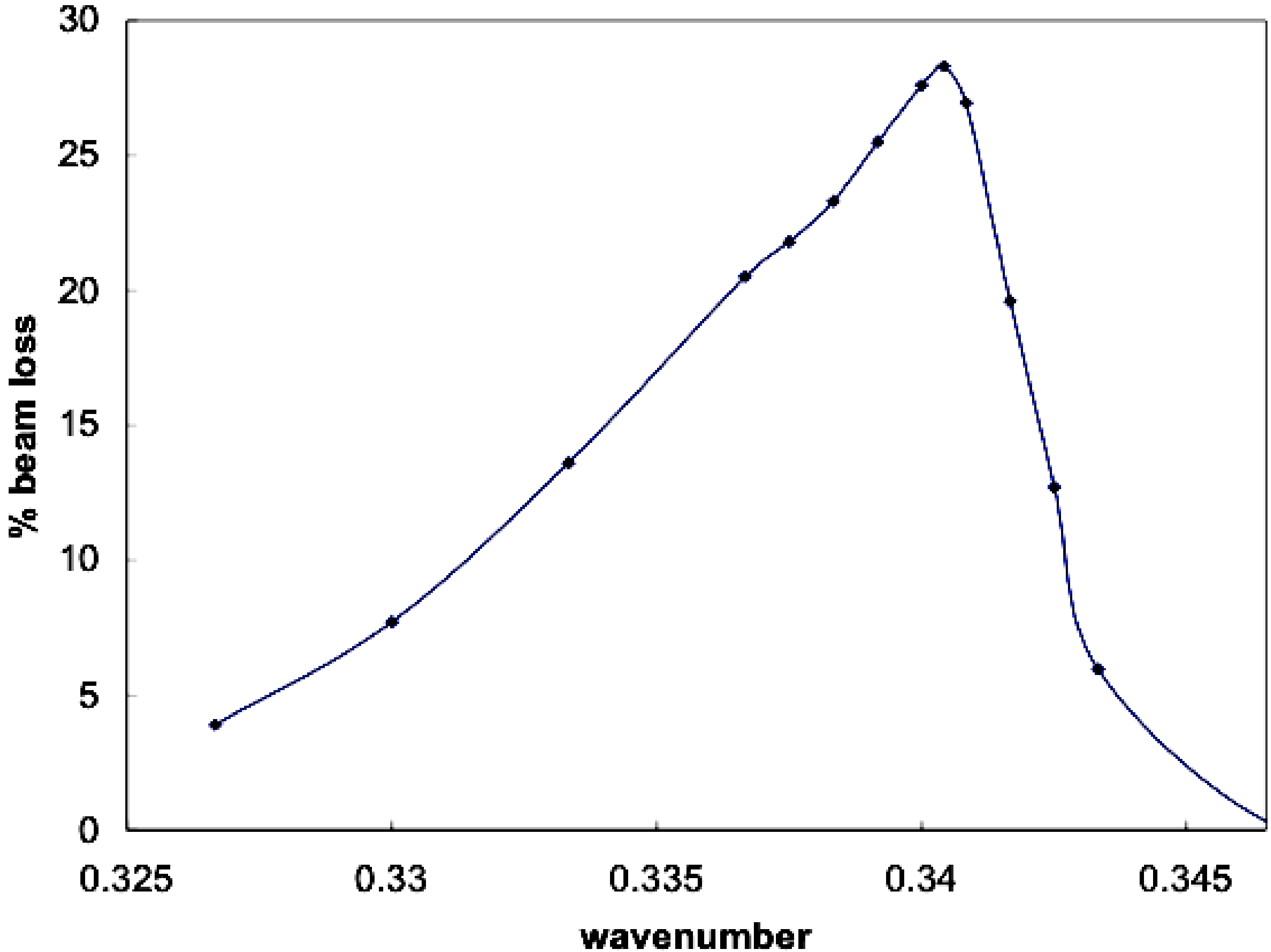
20% n_e with random transverse offsets produces intermediate beam loss, halo, emittance growth



20% n_e with random radial shape variation somewhat worse than const but much better than random amplitude



RESONANT perturbations are more damaging: 0-10% sinusoidally varying n_e resonant with breathing mode



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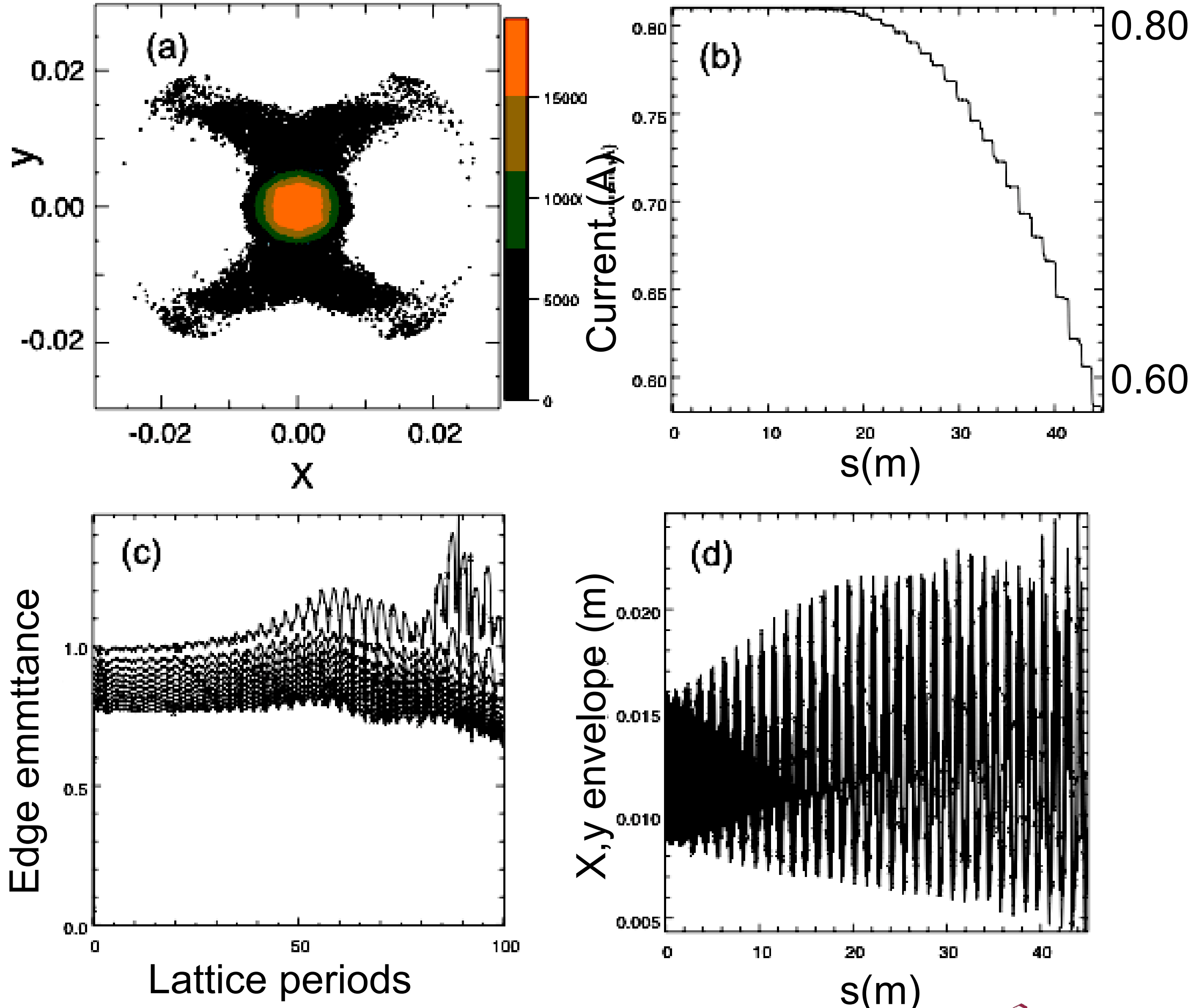
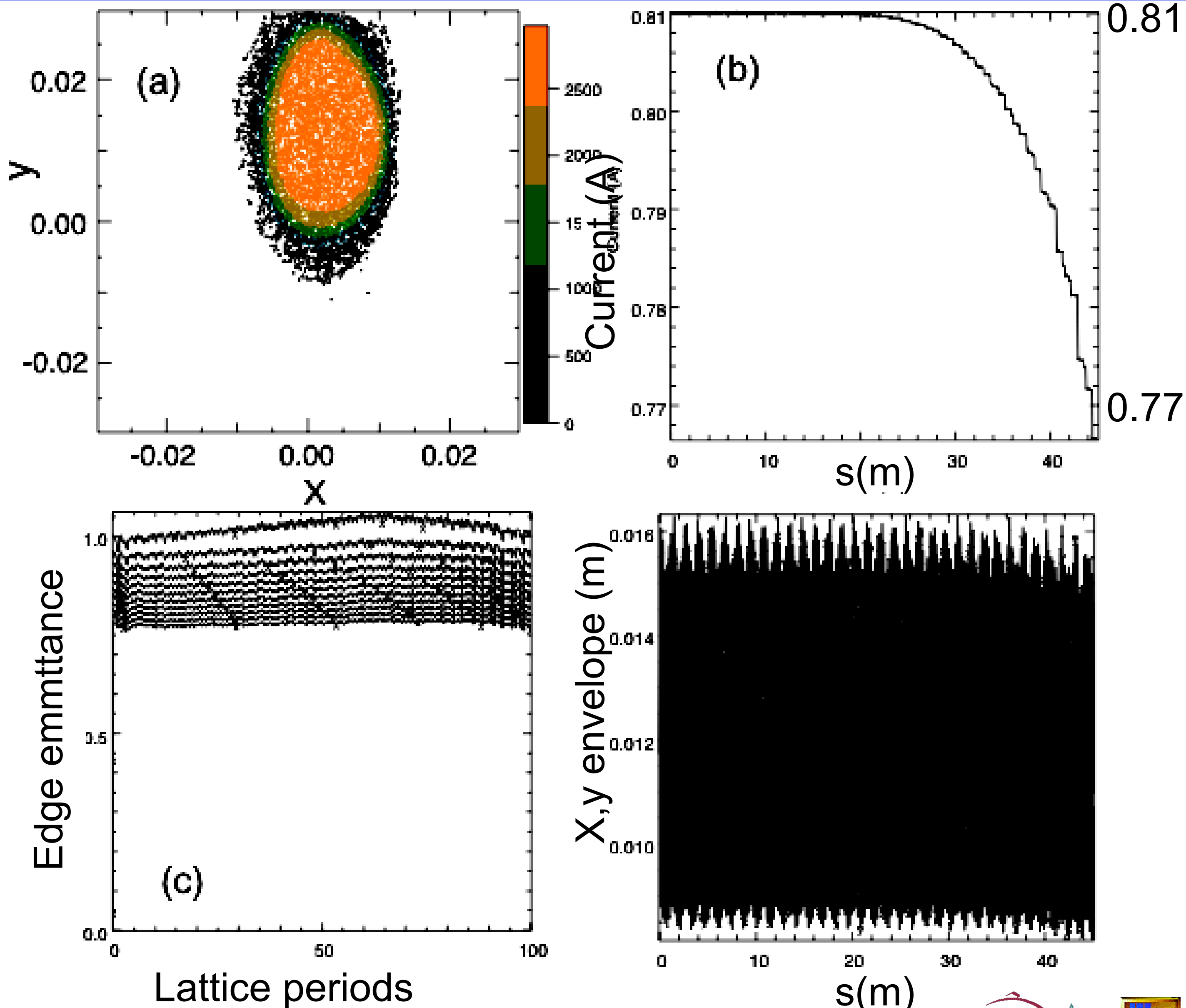
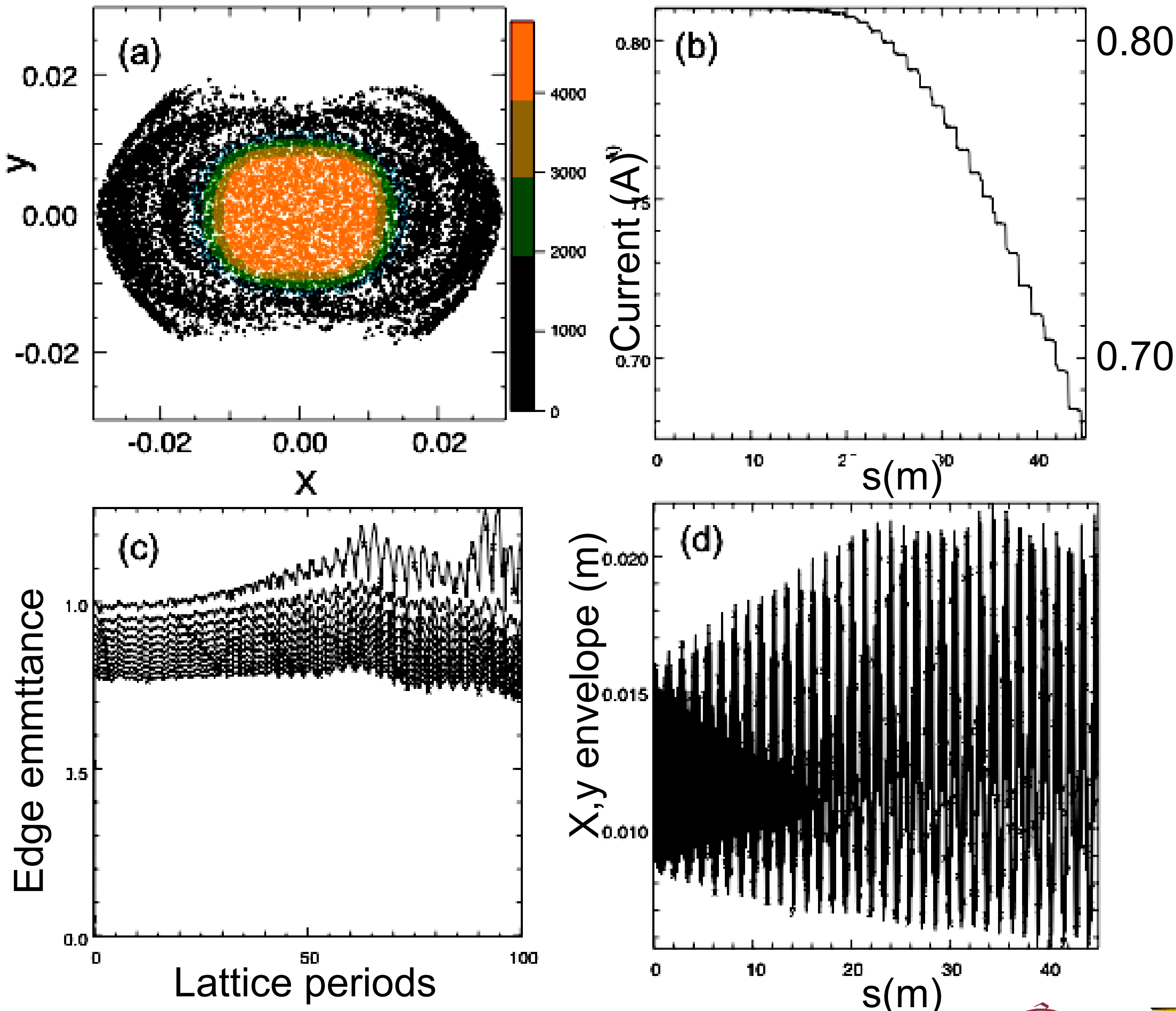


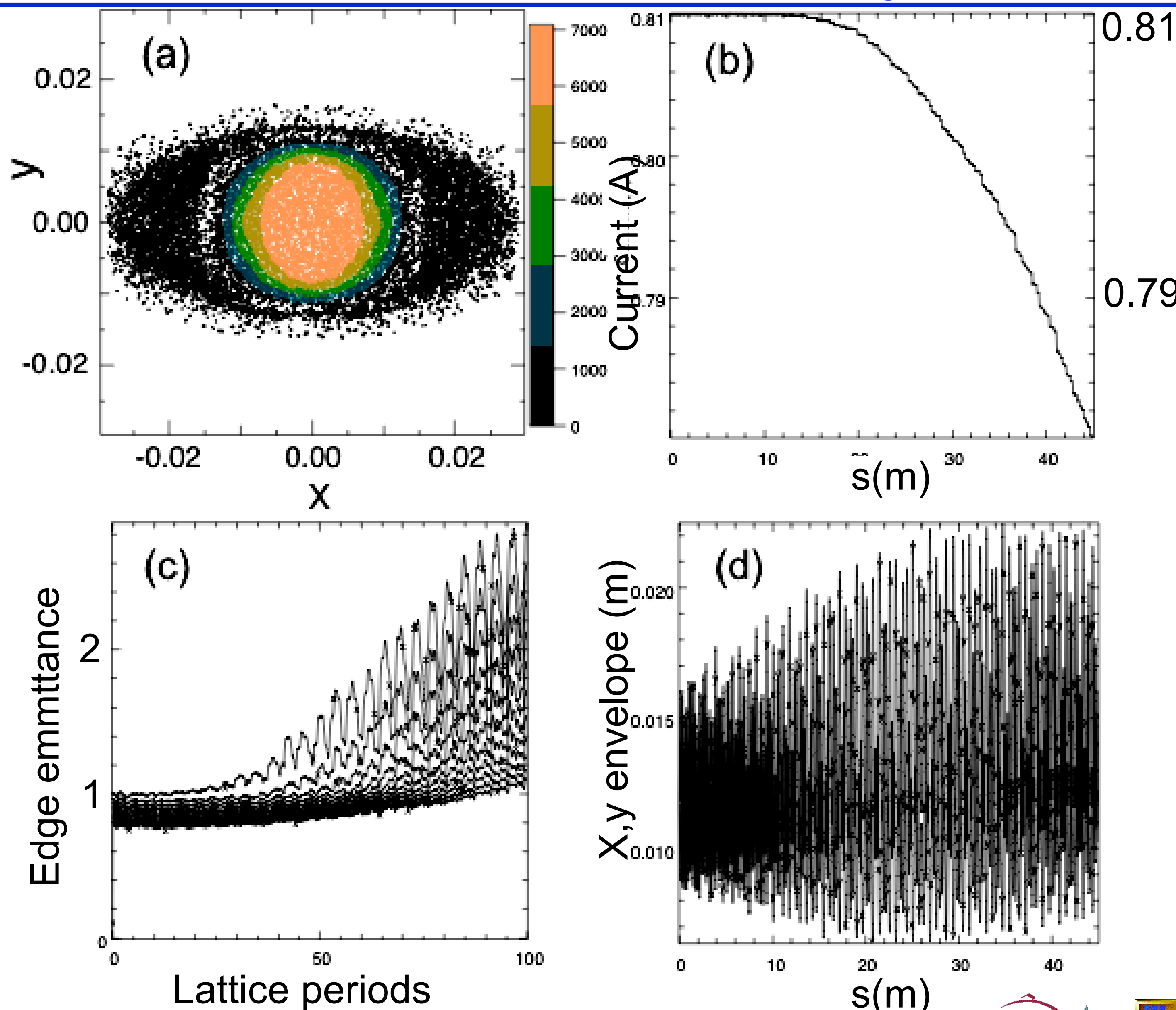
Ecloud offset (10% n_e) displaces ion beam enough for significant scrapeoff but little halo or emittance growth



Sinusoidal radial shape variation (10% n_e, resonant with breathing) less effective than amplitude modulation

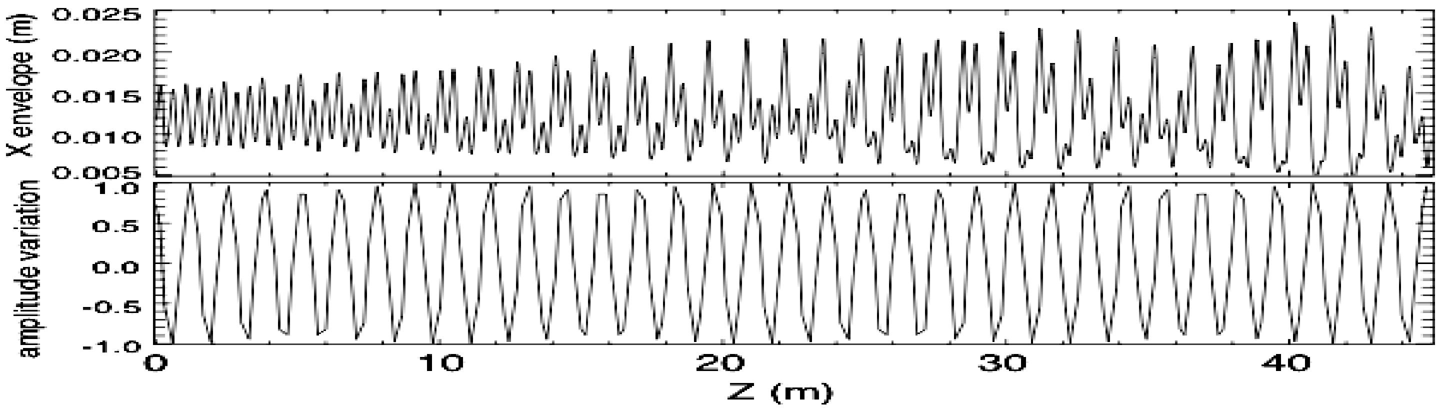


Ellipticity resonant with q-pole oscillation (10% n_e) produces small beam loss but more bulk emittance growth

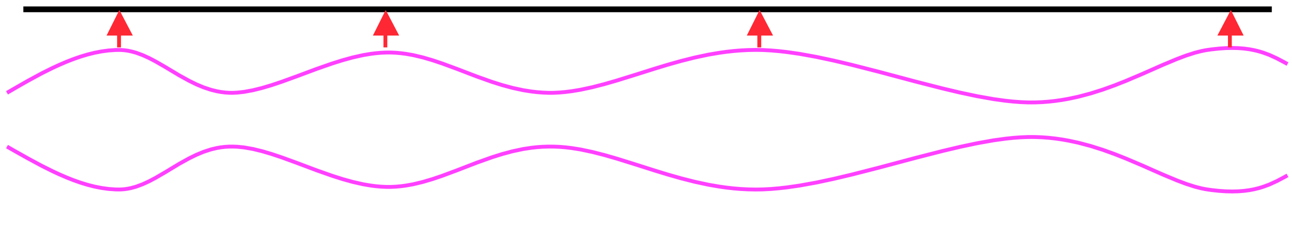


These resonant perturbations are potentially a source of instability

- Ion envelope breathing in phase with e^- oscillations



- Envelope peaks will produce more electrons



- Electrons ~ immobile in beam direction due to quadrupoles
- Perturbation will grow
- Doesn't require const wavenumber (acceleration allowed)

More on instability

- Crude, semi-empirical growth rate (assumptions: coasting beam; wall gas desorption dominates e^- production; neglect neutral time of flight; resonant beam loss $\propto n_e$):

$$\frac{dN_e}{dt} = n_b N_n \langle \sigma v_i \rangle \qquad \frac{dN_n}{dt} = A\Gamma_w \kappa_n$$

with A=area, κ_n = neutrals released per incident ion, N=nV with V=beam volume

- Yields exponential growth with e-folding time:

$$\left[\frac{n_e}{n_b}\frac{Ve}{\langle \sigma v \rangle \kappa_n \Delta I_b}\right]^{1/2}$$

~ 3 μs for simulation parameters (~ τ_b)

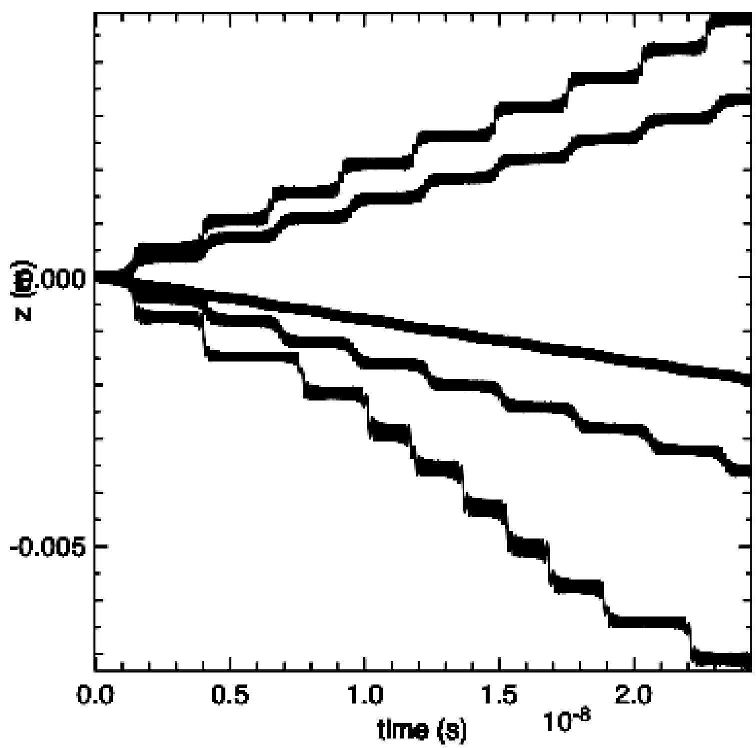
- Growth limited by:
  - Velocity tilt
  - Beam current loss
  - Finite neutral transit time

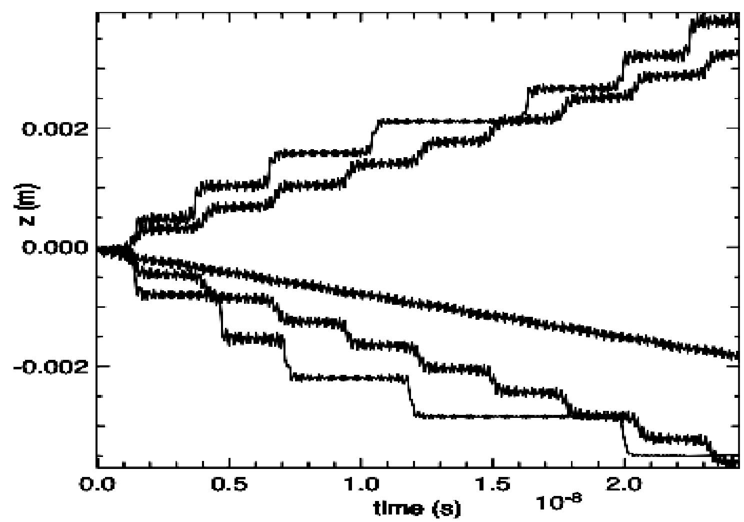
Self-consistent e-i simulation requires technique to bridge timescales

- Need to follow electrons through strongly magnetized and unmagnetized regions $\Rightarrow$ need to deal with electron cyclotron timescale, ~ 10^{-11} sec.
- Ion timescales > 10^{-8} sec.
- Algorithm to bridge: interpolation between full-electron dynamics (Boris mover) and drift kinetics (motion along B plus drifts).
- Properly chosen interpolation allows stepping electrons on bounce timescale (~10^{-9} sec) yet preserves:
  - Drift velocity
  - Parallel dynamics
  - Physical gyroradius

Interpolated mover: first tests meet expectations

- Compare full orbit to interpolated mover (10x dt).
- Single orbit comparisons of some regular and nonadiabatic (chaotic) orbits:
  - Good agreement on drift & bounce velocity, orbit size for regular orbits
  - Expected non-agreement for chaotic orbits (expect similar statistics; not yet tested).





Summary/conclusions

- High current, fill factor, pulse length, unclean walls of HIF induction accelerators $\Rightarrow$ dominant electron sources are ionization of neutrals released from walls
  – except ion-produced secondary electrons for short pulse expts or after drift compression
- Developing self-consistent modeling capability for e-cloud formation, dynamics, effects on ions
- Simulation of dynamics of secondary electrons from ion impacts shows importance of keeping scattered ions
- Simulation of ion evolution with various model electron distributions shows:
  – effect of random amplitude variations > random offsets > const n_e
  – Resonant sinusoidal perturbations more potent, especially amplitude resonant with breathing mode.
  – Ion beams surprisingly robust: 20% const n_e little effect; several percent resonant perturbation needed for significant impact
  – Possible instability (mild) associated with resonant perturbations